North American Journal of Fisheries Management

ISSN: 0275-5947 (Print) 1548-8675 (Online) Journal homepage: https://www.tandfonline.com/loi/ujfm20

Turbidity as a Water Quality Standard for Salmonid Habitats in Alaska

Denby S. Lloyd

To cite this article: Denby S. Lloyd (1987) Turbidity as a Water Quality Standard for Salmonid Habitats in Alaska, North American Journal of Fisheries Management, 7:1, 34-45, DOI: 10.1577/1548-8659(1987)7<34:TAAWQS>2.0.CO;2

To link to this article: https://doi.org/10.1577/1548-8659(1987)7<34:TAAWQS>2.0.CO;2

Published online: 09 Jan 2011.

North American Journal of Fisheries Management 7:34–45, 1987

Turbidity as a Water Quality Standard for Salmonid Habitats in Alaska

DENBY S. LLOYD[1]

Alaska Department of Fish and Game, Habitat Division
333 Raspberry Road, Anchorage, Alaska 99518, USA

Abstract.—Evidence both of trophic level changes induced by reduction in light penetration and of more direct effects of sediment and turbidity on aquatic life indicates that turbidity constitutes a valid and useful water quality standard that can be used to protect aquatic habitats from sediment pollution. A review of studies conducted in Alaska and elsewhere indicated that water quality standards allowing increases of 25 or 5 nephelometric turbidity units above ambient turbidity in clear coldwater habitats provide moderate and relatively high protection, respectively, for salmonid fish resources in Alaska. Even stricter limits may be warranted to protect extremely clear waters, but such stringent limits apparently are not necessary to protect naturally turbid systems.

Turbidity has been described as a major water quality characteristic affecting freshwater fish communities (Judy et al. 1984), yet there has been little published literature expressly analyzing the use of specific turbidity criteria as water quality standards to protect aquatic habitats and fish from sediment pollution. In this paper, I review the available literature on turbidity in cold freshwater habitats beyond that discussed in Lloyd et al. (1987, this issue) and evaluate the efficacy of water quality standards that are based on specific turbidity criteria, particularly those currently used in Alaska. The justification and implementation of appropriate standards are important to protect fish resources from habitat degradation caused by this common form of pollution.

Turbidity is an optical property of water wherein suspended and some dissolved materials such as clay, silt, finely divided organic and inorganic matter, plankton, and other microscopic organisms cause light to be scattered and absorbed rather than transmitted in straight lines (APHA et al. 1980). Modern nephelometric techniques measure the scattering of light in a sample of water at an angle of 90° to the path of incident light; therefore absorption of light has little effect in more recent turbidity measures (Vanous et al. 1982). Measurements of turbidity have been developed to quickly estimate the amount of sediment within a sample of water (Truhlar 1976; Schroeder et al. 1981; Earhart 1984), and they are also used to describe the effect of suspended sediment in blocking the transmission of light through a body of water.

Effects of Turbidity and Suspended Sediment on Salmonids

An increase in turbidity has been shown to dramatically reduce light penetration in both lakes and streams in Alaska and elsewhere; it is associated with decreased production and abundance of plant material (primary production), decreased abundance of fish food organisms (secondary production), and decreased production and abundance of fish (Lloyd et al. 1987). There also are definable relations between turbidity and the concentration of suspended sediments (Lloyd et al. 1987) that enable turbidity to be used as a reasonable estimator of suspended sediment concentration (SSC). These relationships can be important tools given that high SSC has been directly related to adverse impacts on aquatic systems beyond those directly attributable to turbidity.

In addition to the studies conducted in Alaska, there is a large, albeit disjointed, body of literature on the effects of turbidity and suspended sediments. Reviews of much of this literature have been provided by Hollis et al. (1964), Sherk (1971), Sorensen et al. (1977), Stern and Stickle (1978), Farnworth et al. (1979), Muncy et al. (1979), and Wilber (1983). In an often-cited study, Wallen (1951) reported that lethal levels of turbidity, then expressed in parts per million, range in the 10s to 100s of thousands of parts per million (ppm). These high levels of turbidity required to kill fish led Wallen (1951) to conclude that natural turbidity does not represent a lethal threat to fish. Wallen's information, however, was developed primarily from tests of acute effects on warmwater fishes and

[1] Present address: North Pacific Fishery Management Council, Post Office Box 103136, Anchorage, Alaska 99510, USA.

likely is not applicable to the coldwater salmonids prevalent in Alaska, other western and northern states, and Canadian provinces. Moreover, a study on largemouth bass (*Micropterus salmoides*) and green sunfish (*Lepomis cyanellus*) contained data that indicated lower levels of turbidity such as 4–16 Jackson turbidity units (JTU) can alter fish behavior (Heimstra et al. 1969). Also, relatively low turbidity can reduce the feeding efficiency of bluegills (*Lepomis macrochirus*; Vinyard and O'Brien 1976; Gardner 1981).

Relatively low turbidity or SSC may either stress these fish, alter their behavior patterns, or kill them. Lloyd et al. (1987) described impacts observed in Alaska, and a summary of relevant literature from studies conducted outside Alaska on the direct effects of turbidity or sediments measured as suspended material on salmonid fishes is presented in Table 1. Particularly noteworthy is the fact that even low turbidities near 10–25 nephelometric turbidity units (NTU), and suspended sediment concentrations near 35 ppm can have deleterious effects on fish (Bachmann 1958; Olson et al. 1973; Smith and Sykora 1976; Berg 1982; Bachman 1984; Sigler et al. 1984; Berg and Northcote 1985).

The European Inland Fisheries Advisory Commission (EIFAC 1964) concluded that waters containing 0–25 ppm chemically inert solids should not adversely affect freshwater fisheries, but that an SSC of 25–80 ppm may lower the production of fish; waters containing an SSC above 80 ppm are unlikely to support good fisheries. Moreover, the commission emphasized that "the spawning grounds of salmon and trout require special consideration and should be kept as free as possible from finely divided sediments." Gammon (1970), in a report to the U.S. Environmental Protection Agency on stream studies conducted in Indiana, stated that the suspended solids criteria proposed by EIFAC may be too liberal for fish populations in the United States.

A turbidity level of 10 NTUs can cause significant declines in feeding rate, food assimilation, and reproductive potential of *Daphnia pulex* (McCabe and O'Brien 1983). Robinson (1957) found that reproduction of cladocerans was reduced at clay and charcoal concentrations of 82–392 ppm. Arruda et al. (1983) observed that suspended sediment concentrations of 50–100 mg/L reduced the algal carbon ingested by cladocerans to potential starvation levels. Cladocerans constitute an important food item for salmonid fishes and effects on these zooplankton can translate to reduced food availability or quality for fish.

Water Quality Standards in Alaska

Water quality standards impose limits on allowable, human-induced alterations of natural waters. These limits are specified for various characteristics with respect to the designated use or classification of a particular body of water. Most of Alaska's fresh waters have been classified as suitable for drinking water supply and other consumptive uses. The receiving water standard for turbidity in waters suitable for drinking water supply states that waters:

> Shall not exceed 5 NTU above natural conditions when the natural turbidity is 50 NTU or less, and not have more than 10% increase in turbidity when the natural condition is more than 50 NTU, not to exceed a maximum increase of 25 NTU [AAC 1985].

Although few, if any, waters in Alaska are designated only for use by fish and wildlife because of their already more restrictive classification for drinking water supply, Alaska's water quality standards do contain a separate standard for waters classified for the growth and propagation of fish, shellfish, other aquatic life, and wildlife, including waterfowl and furbearers. In receiving waters, streams:

> Shall not exceed 25 NTU above natural condition level. For all lake waters, shall not exceed 5 NTU over natural conditions [AAC 1985].

For simplicity in considering allowable increases of turbidity in clearwater systems, we can restate the above standards: for drinking water, no more than 5 NTU above natural; for fish and wildlife, no more than 25 NTU above natural in streams and no more than 5 NTU above natural in lakes.

Alaska has no numerical standard for SSC in drinking water supplies, but the state does have a generic, narrative standard for sediment.

> No measurable increase in concentrations of sediment, including settleable solids, above natural levels. [AAC 1985.]

The sediment standard for the propagation of fish and wildlife is much more complex and difficult to enforce.

> The percent accumulation of fine sediment in the range of 0.1 mm to 4.0 mm in the gravel bed of waters utilized by anadromous or resident fish for spawning may not be increased more than 5% by weight over natural condition (as shown from grain size accumulation graph). In no case may the 0.1 mm to 4.0 mm fine sediment range in the gravel bed of waters utilized by anadromous or resident fish for spawning exceed a maximum of 30% by weight (as shown from grain size accumulation graph). . . . In all other surface waters

TABLE 1.—Some reported effects of turbidity and suspended sediment concentrations on salmonids outside Alaska.

Effect	Species[a] (life stage)	Location	Reported turbidity[b] or suspended sediment concentration	Reference
Fatal (96-h LC_{50})	Coho salmon (juveniles)	Washington	1,200 mg/L	Noggle (1978)
Fatal (96-h LC_{50})	Coho salmon (juveniles)	Washington	509; 1,217 mg/L	Stober et al. (1981)
Fatal (96-h LC_{50})	Chinook salmon (juveniles)	Washington	488 mg/L	Stober et al. (1981)
Reduced survival (marked)	Chum salmon (eggs)	British Columbia	97 mg/L	Langer (1980)
Reduced survival (marked)	Rainbow trout (eggs)	Great Britain	110 mg/L	Scullion and Edwards (1980)
Reduced survival (marked)	Rainbow trout (eggs)	Oregon	1,000–2,500 ppm	Campbell (1954)
Reduced survival (marked)	Rainbow trout (juveniles)	Great Britain	270 ppm	Herbert and Merkens (1961)
Reduced survival (marked)	Rainbow trout (juveniles)	Great Britain	200 ppm	Herbert and Richards (1963)
Reduced survival (marked)	Rainbow trout (juveniles)	Oregon	1,000–2,500 ppm	Campbell (1954)
Reduced survival (slight)	Rainbow trout (juveniles)	Great Britain	90 ppm	Herbert and Merkens (1961)
Reduced survival (marked)	Coho salmon (juveniles)	Pennsylvania	6; 12 mg Fe/L (15–27 JTU)	Smith and Sykora (1976)
Reduced survival (marked)	Coho salmon (adults)	Washington	1,400–1,600 mg/L	Stober et al. (1981)
Reduced abundance (marked)	Brown trout	Great Britain	1,000; 6,000 ppm	Herbert et al. (1961)
Reduced abundance (marked)	Lake trout	Northwest Territories	<10 FTU	McCart et al. (1980)
Reduced growth (marked)	Brook trout (juveniles)	Pennsylvania	50 mg Fe/L (86 JTU)	Sykora et al. (1972)
Reduced growth (slight)	Brook trout (juveniles)	Pennsylvania	12 mg Fe/L (32 JTU)	Sykora et al. (1972)
Reduced growth (slight)	Rainbow trout (juveniles)	Great Britain	50 ppm	Herbert and Richards (1963)
Reduced growth	Coho salmon (juveniles)	Idaho	25 NTU	Sigler et al. (1984)
Reduced growth (marked)	Arctic grayling (juveniles)	Yukon	1,000 mg/L	McLeay et al. (1984)
Reduced growth (slight)	Arctic grayling (juveniles)	Yukon	100; 300 mg/L	McLeay et al. (1984)
Reduced food conversion	Rainbow trout (juveniles)	Arizona	<70 JTU	Olson et al. (1973)
Reduced feeding (cessation)	Coho salmon (juveniles)	Washington	300 mg/L	Noggle (1978)
Reduced feeding	Coho salmon (juveniles)	Washington	100 mg/L	Noggle (1978)
Reduced feeding	Coho salmon (juveniles)	British Columbia	10–60 NTU	Berg (1982), Berg and Northcote (1985)
Reduced feeding (cessation)	Cutthroat trout	Idaho	35 ppm	Bachmann (1958)
Reduced feeding	Brown trout	Pennsylvania	7.5 NTU	Bachman (1984)
Reduced feeding	Rainbow trout (juveniles)	Arizona	70 JTU	Olson et al. (1973)
Reduced feeding	Arctic grayling (juveniles)	Yukon	100; 300; 1,000 mg/L	McLeay et al. (1984)
Reduced condition factor	Rainbow trout (juveniles)	Great Britain	110 mg/L	Scullion and Edwards (1980)
Altered diet (terrestrial instead of aquatic)	Rainbow trout (juveniles)	Great Britain	110 mg/L	Scullion and Edwards (1980)

TABLE 1.—Continued.

Effect	Species[a] (life stage)	Location	Reported turbidity[b] or suspended sediment concentration	Reference
Stress (increased plasma cortisol, hematocrit, and susceptibility to pathogens)	Coho salmon (juveniles)	Oregon	500 mg/L	Redding and Schreck (1980)
	Steelhead (juveniles)		2,000 mg/L	
Stress (increased metabolic rate, susceptibility to toxicants)	Arctic grayling (juveniles)	Yukon	300 mg/L	McLeay et al. (1984)
Stress (increased plasma glucose)	Arctic grayling (juveniles)	Yukon	50 mg/L	McLeay et al. (1983)
Stress (respiratory distress)	Coho salmon (juveniles)	Pennsylvania	6; 12 mg Fe/L (15–27 JTU)	Smith and Sykora (1976)
Stress (increased ventilation)	Brook trout (juveniles)	Lake Superior	231 NTU	Carlson (1984)
Disease (fin rot)	Rainbow trout (juveniles)	Great Britain	270 ppm	Herbert and Merkens (1961)
Disease (fin rot)	Rainbow trout (juveniles)	Great Britain	100; 200 ppm	Herbert and Merkens (1961)
Avoidance	Chinook salmon (adults)	California	"Natural turbidity"	Sumner and Smith (1940)
Avoidance	Chinook salmon (adults)	Washington	650 mg/L	Whitman et al. (1982)
Avoidance	Chinook salmon (adults)	Washington	350 mg/L	Brannon et al. (1981)
Avoidance (sensitivity)	Lake trout	Lake Superior	6 FTU	Swenson (1978)
Avoidance	Coho salmon (juveniles)	Washington	70 NTU	Bisson and Bilby (1982)
Avoidance	Coho salmon, steelhead (juveniles)	Idaho	22–265 NTU	Sigler (1980), Sigler et al. (1984)
Displacement	Coho salmon, steelhead (juveniles)	Idaho	40–50 NTU	Sigler (1980)
Displacement	Arctic grayling (juveniles)	Yukon	300; 1,000 mg/L	McLeay et al. (1984)
Displacement	Rainbow trout (juveniles)	Great Britain	110 mg/L	Scullion and Edwards (1980)
Altered behavior (feeding)	Trout	[c]	25 JTU	Langer (1980)
Altered behavior (less use of overhead cover)	Brook trout	Wisconsin	7 FTU	Gradall and Swenson (1982)
Altered behavior (visual)	[c]	[c]	25–30 JTU	Bell (1984)
Altered behavior (visual)	Coho salmon (juveniles)	British Columbia	10–60 NTU	Berg (1982), Berg and Northcote (1985)
Altered behavior (loss of territoriality)	Coho salmon (juveniles)	British Columbia	10–60 NTU	Berg (1982), Berg and Northcote (1985)
Altered behavior (listlessness)	Coho salmon (juveniles)	Pennsylvania	6; 12 mg Fe/L (15–27 JTU)	Smith and Sykora (1976)
Change in body color	Arctic grayling (juveniles)	Yukon	300; 1,000 mg/L	McLeay et al. (1984)
Change in body color	Coho salmon (juveniles)	Pennsylvania	6; 12 mg Fe/L (15–27 JTU)	Smith and Sykora (1976)
Reduced tolerance to saltwater	Chinook salmon (juveniles)	Washington	3,109 mg/L	Stober et al. (1981)

[a] Arctic grayling (*Thymallus arcticus*)
Brook trout (*Salvelinus fontinalis*)
Brown trout (*Salmo trutta*)
Chinook salmon (*Oncorhynchus tshawytscha*)
Chum salmon (*Oncorhynchus keta*)
Coho salmon (*Oncorhynchus kisutch*)
Cutthroat trout (*Salmo clarki*)
Lake trout (*Salvelinus namaycush*)
Rainbow trout (*Salmo gairdneri*)
Steelhead (anadromous *S. gairdneri*)

[b] Formazin (FTU), Jackson (JTU), and nephelometric (NTU) turbidity units.

[c] Information not available.

TABLE 2.—Numerical turbidity standards for protection of fish and wildlife aquatic habitats in Alaska and other states (ADEC 1978; API 1980).

State	Turbidity (NTU or JTU)[a]
Alaska	25 units above natural in streams 5 units above natural in lakes
California	20% above natural, not to exceed 10 units above natural
Idaho	5 units above natural
Minnesota	10 units
Montana	10 units (5 above natural)[b]
Oregon	10% above natural
Vermont	10 units (cold water)
Washington	25 units above natural (5 and 10 above natural)[c]
Wyoming	10 units above natural

[a] Nephelometric (NTU) and Jackson (JTU) turbidity units are roughly equivalent (USEPA 1983).

[b] Montana places the more stringent limit on waters containing salmonid fishes.

[c] API (1980) reports different values in Washington for "excellent" and "good" classes of water.

> no sediment loads (suspended or deposited) which can cause adverse effects on aquatic animal or plant life, their reproduction or habitat. [AAC 1985.]

By definition, turbidity and SSC are closely intertwined. Information summarized by Lloyd et al. (1987) indicated that a turbidity standard can be used to address the effects of turbidity as an optical property of water and as an indicator of SSC. The effects of sedimentation on lake and stream bottoms could then be addressed by separate, enforceable settleable solids or streambed standards. Regardless of whether such changes are made to water quality standards for sediment, there is still a need to establish or reaffirm the levels of turbidity, and consequently SSC, that are appropriate as standards for regulating human-induced impacts on aquatic systems.

Light Penetration and Productivity

An acceptable turbidity standard must do two things to protect aquatic habitats: (1) prevent a loss of aquatic productivity and (2) cause no lethal or chronic sublethal effects on fish and wildlife. With reference to Alaska's current standard for the propagation of fish and wildlife, a 5-NTU increase in turbidity in a clear-water lake may reduce the productive volume of that lake by about 80%, and a 25-NTU increase in a clear-water stream 0.5 m deep may reduce plant production by about 50% (Lloyd et al. 1987). This standard for protection of fish and wildlife in streams is more lenient than the 10-JTU criterion previously recommended by the U.S. Federal Water Pollution Control Administration (USFWPCA 1968). Turbidity standards used in Alaska and in other western and northern states indicate that Alaska currently allows liberal increases of turbidity over natural conditions in streams (Table 2). It is interesting to note, however, that a recent telephone survey of state and provincial agencies of the United States and Canada indicated that no adequate justification has yet been developed for these standards outside of Alaska (Peterson et al. 1985).

Alaska's current drinking water standard of 5 NTUs above ambient levels in clear-water lakes and streams also may allow a reduction of primary plant production—but not to the extent that the 25-NTUs-over-ambient standard for fish and wildlife would allow in streams. For comparison, a 5-NTU increase in turbidity in a clear stream 0.5 m deep may reduce primary production by 13% or more, depending on stream depth (Lloyd et al. 1987).

Absolute turbidities of 4–8 NTUs and above may hamper the efficient management of fisheries in Alaska because aerial observers cannot see into the streams and estimate returns of adult salmon, and absolute turbidities of 8 NTUs and higher have been shown to reduce sport fishing in fish-bearing waters in Alaska (Lloyd et al. 1987). The Alaska Interagency Placer Mining Guidelines (ADEC et al. 1984) use turbidity of 3 NTUs or less as a criterion for establishing "high priority" streams. Application of a 5-NTUs-above-ambient standard would bring total turbidities in these streams to 8 NTUs, the level at which recreational fishing may decline, and at or near the level at which efficiency of aerial surveys of spawning salmon may be affected.

Suspended Sediment

There is evidence that high SSC is lethal to fish, and that somewhat lower levels of SSC and turbidity cause chronic, sublethal effects such as loss or reduction of sight-feeding capabilities, reduced growth, increased stress, and interference with environmental cues necessary for orientation in migrations (Table 1). Furthermore, suspended sediment may facilitate the transport of heavy metals and other pollutants (LaPerriere et al. 1985).

Several organizations have made recommendations for appropriate SSC in fish-bearing waters. By use of equation (9), $T = 0.44(SSC)^{0.858}$, of Lloyd et al. (1987), which relates turbidity (T) to suspended sediment concentration (SSC) in waters throughout Alaska, these recommendations can be translated into approximate turbidity criteria (Ta-

TABLE 3.—Recommended levels of suspended sediment concentration for the protection of fish habitat and translation of those levels to turbidity values for Alaskan waters. (NTU = nephelometric turbidity units.)

Reference	Level of protection from suspended sediment	Recommended suspended sediment concentration limitation (mg/L)	Translated maximum turbidity level state-wide[a] (NTU)	Translated maximum turbidity level for interior Alaska[b] (NTU)
EIFAC (1964)	High	0–25	7	25
Alabaster (1972)	Moderate	26–80	19	77
NAS and NAE (1973)	High	0–25	7	25
	Moderate	26–80	19	77
Alabaster and Lloyd (1980)	High	0–25	7	25
	Moderate	26–80	19	77
Newport and Moyer (1974)	High	0–25	7	25
	Moderate	26–100	23	95
Wilber (1969, 1983)	High	0–30	8	30
	Moderate	30–85	20	81
Hill (1974)	High	0–10	3	10
DFO (1983)	High	0	0	0
	Moderate	1–100	23	95

[a] Derived from equation (9) in Lloyd et al. (1987).
[b] Derived from equation (12) in Lloyd et al. (1987).

ble 3). Recommendations for a "moderate" level of protection (SSC up to 100 mg/L) roughly translate into turbidity values of up to 23 NTUs, close to Alaska's current standard of 25 NTUs above natural conditions for the protection of fish and wildlife. Recommendations for a "high" level of protection (0–25 mg/L) roughly translate into turbidity values ranging up to 7 NTUs, approximating Alaska's drinking water standard of 5 NTUs above natural conditions. Application of the present drinking water standard to waters in Alaska would conform to a consensus view of a "high" level of protection for fish from suspended sediments.

By use of equation (12), $T = 1.103(SSC)^{0.968}$, from Lloyd et al. (1987) for interior Alaskan streams, "moderate" and "high" levels of protection from suspended sediment would translate into the higher turbidities of 95 and 25 NTUs, respectively (see Table 3), but these turbidities are too high to prevent light extinction and the accompanying decrease in the production of plants, fish food, and fish. Moreover, these higher turbidities could be expected to interfere with sight feeding of fish, angler success, and aerial escapement surveys.

Limitations to Existing Information

Assumptions made about the importance of aquatic primary production in streams may not be completely applicable to vegetated watersheds which likely rely more heavily upon organic material derived from terrestrial sources (Chapman and Demory 1963; Chapman 1966). In addition, little work has been performed on the capacity of compensatory mechanisms to increase photosynthetic efficiency under low-light or turbid conditions (McIntire 1973; Hecky 1984; Hecky and Guildford 1984; Van Nieuwenhuyse and LaPerriere 1986), on the effect of organic staining of water on light penetration and turbidity (Brezonik 1978; Witte et al. 1982), or on the influence of increased or depressed nutrient concentrations caused by the same sediments that decrease light availability (Tilzer et al. 1976; Jackson and Hecky 1980).

Current information on relationships between turbidity and suspended sediment concentration is understandably tentative for at least four reasons.

(1) It is well known that the amount of turbidity produced per unit of suspended sediment concentration depends on sediment particle size, shape or angularity, and refractive index. Furthermore, these relationships will change with changes in hydrologic or hydraulic conditions as well as with differences in the geologic composition of the sediment source (Duchrow and Everhart 1971; Kunkle and Comer 1971; Beschta 1980; Milhous 1982).

(2) Measurements of turbidity may include some settleable solids, depending on the amount of settling that takes place before the sample is taken (Duchrow and Everhart 1971). Moreover, it is sometimes difficult to distinguish adverse im-

pacts to aquatic habitats caused by suspended materials from those caused by settleable materials.

(3) As illustrated in a recent study on placer-mined streams in interior Alaska by Toland (1984), the relationship between turbidity and SSC may change along a downstream gradient from a sediment source. Specifically, Toland found that, within the first 24 km downstream from placer-mine discharges on the Chatanika River, each 1 mg/L of suspended sediment produced less than 1 NTU of turbidity but, at points further downstream, each 1 mg/L of suspended sediment produced more than 1 NTU of turbidity (within the range of 10–150 units each for NTU and mg/L). This observation follows the intuitive notion that larger particles, which generally produce less turbidity per unit concentration than smaller particles, gradually settle out, thus shifting the turbidity versus SSC relationship to a higher NTU per unit SSC in reaches progressively further downstream (Ritter and Brown 1971).

(4) Depending on geomorphic, hydrologic, and hydraulic factors, different streams are able to accommodate different levels of sediment input and may naturally support different biotic communities.

Different species and even different life stages of species are susceptible to adverse effects from different levels of sediment and to sediments of different sizes. Salmonids are generally more susceptible to acute and chronic effects of sediment than are many species of warmwater fishes; however, even among salmonids some species may be more sensitive than others, and the sensitivity of their eggs and juvenile stages seemingly exceeds that of adults.

Evaluation of Alternative Standards

Several authors have suggested the need for standards other than simple turbidity criteria to control pollution by sediment. Wilson (1957) proposed that turbidity standards be based on a percentage increase above normal low-flow conditions. Tarzwell (1957) recommended that turbidity standards be altered to state that some percentage of incident light at the surface be allowed to reach a specified depth, standardized to a time between 1100 and 1300 hours. The National Academy of Sciences and National Academy of Engineering (NAS and NAE 1973) recommended that the depth of light penetration not be decreased by more than 10%, and that suspended sediment concentrations be limited to specific values, as outlined for the National Academy of Sciences in Table 3.

Cairns (1968) recognized the value of more flexible approaches but suggested that truly responsive regulations must be developed on a drainage-by-drainage basis and should change with stream-flow and other temporal characteristics. A significant problem with this approach, however, is that implementation and enforcement of such standards would require enormous baseline studies and almost continuous surveillance and monitoring. There is a question whether such an approach is feasible in Alaska or elsewhere.

The U.S. Environmental Protection Agency (USEPA 1976) recommended a joint standard for turbidity and solids.

> Freshwater fish and other aquatic life: Settleable and suspended solids should not reduce the depth of the compensation point for photosynthetic activity by more than 10 percent from the seasonally established norm for aquatic life.

This standard suffers from several deficiencies. First, the standard does not consider impacts associated with sediment deposited on the bottom, even though it mentions settleable solids; second, in relation to the water column, the standard does not address specific levels of SSC and places a severe burden on regulatory agencies to define a "seasonally established norm" for the compensation point. Third, as emphasized by Thurston et al. (1979), compensation point is of little value in streams, particularly where the water is so clear and shallow that light naturally penetrates all the way to the bottom. Thurston et al. (1979) recommended that separate solids standards (mg/L) and turbidity standards (NTU) be developed, designed to facilitate ease of measurement.

Any alternative standards to turbidity should account for both major aspects of turbidity—the extinction of light and the presence of suspended sediment. Direct measurement of both of these characteristics is possible; however, it should be recognized that the measure of turbidity was developed to make such estimates easier. Light penetration can be measured in situ with portable photometers and extinction coefficients calculated with simple graphs or equations, but discrete samples cannot be removed and analyzed separately. Sediment concentration can be sampled in the field and measured gravimetrically in a laboratory, but filtering, drying, and weighing procedures are required.

Establishment of any alternative standards will require considerable research and justification, as well as regulatory support. It is premature to judge whether such alternatives would provide more effective regulatory tools than those current turbidity standards now offer, particularly if it is considered that turbidity standards can be tiered or graded (if necessary) to ambient water quality conditions and the level of protection desired for a body of water.

Conclusions

The strength of turbidity standards lies in the easy measurement, from discrete water samples, of an estimator for both light penetration and suspended sediment concentration. Relationships between turbidity and light penetration appear to be accurate and consistent, and the occurrence of even low turbidity has demonstrable and dramatic effects on aquatic plant production. These relationships and effects result in decreased production of zooplankton and macroinvertebrates, decreased abundance and production of fish, reduced angler use and success, and decreased efficiency of some fish management techniques. Relationships between turbidity and concentrations of suspended sediment are much less exact and less consistent; however, low levels of turbidity appear to correspond to sediment concentrations that can adversely affect coldwater salmonids.

Turbidity criteria, then, constitute reasonable water quality standards. Although turbidity is not a direct measure of either light penetration (Phinney 1959; Austin 1974) or suspended sediment concentration (Pickering 1976), it has been shown to be a very useful indicator of these characteristics (Gibbs 1974; Ritter and Ott 1974). Use of turbidity standards in the regulation of water quality is justified much in the same way that the density of fecal coliform bacteria is widely used as a water quality standard indicating the possible presence and concentration of other harmful bacteria. Reasonable turbidity criteria that are established to protect aquatic habitats from decreased light penetration also protect them from high concentrations of suspended sediments and possibly heavy metals. Separate settleable solids or streambed standards could then be applied to protect aquatic habitats from the impacts of heavier sediments on benthic substrates.

On the basis of current information, the continued application of Alaska's present water quality standard for the propagation of fish and wildlife (25 NTUs above natural conditions in streams and 5 NTUs in lakes) can be expected to provide a moderate level of protection for clear coldwater habitats. A higher level of protection would require a more restrictive turbidity standard, perhaps similar to the one currently applied to drinking water in Alaska (5 NTUs above natural conditions in streams and lakes). Even stricter limits may be warranted to protect extremely clear waters, due to the dramatic initial impact of turbidity on light penetration (Lloyd et al. 1987). However, such stringent limits do not appear to be necessary to protect naturally turbid systems where it may be possible to establish tiered or graded standards based on ambient water quality.

Acknowledgments

The author gratefully acknowledges the assistance of J. D. LaPerriere and J. P. Koenings for sharing information on the effects of turbidity in Alaskan waters, L. L. Trasky and K. A. Sundberg for providing the original impetus to conduct this review, B. H. Baker and J. A. Clark for supporting its completion, and J. L. Barker and K. J. Farnham for library assistance in collecting turbidity-related literature.

References

AAC (Alaska Administrative Code). 1985. Water quality standards. AAC, Title 18, Chapter 70, Juneau.

ADEC (Alaska Department of Environmental Conservation). 1978. Nationwide listing of parameters: turbidity, total dissolved solids, settleable solids, and suspended solids for waters suitable for fishing, wildlife, and recreation. ADEC, Juneau.

ADEC (Alaska Department of Environmental Conservation), Department of Natural Resources, and Department of Fish and Game. 1984. Interagency placer mining guidelines. Juneau.

Alabaster, J. S. 1972. Suspended solids and fisheries. Proceedings of the Royal Society of London B Biological Sciences 180:395–406.

Alabaster, J. S., and R. Lloyd. 1980. Water quality criteria for freshwater fish. Butterworth, London.

APHA (American Public Health Association), American Water Works Association, and Water Pollution Control Federation. 1980. Standard methods for the examination of water and wastewater, 15th edition. APHA, Washington, D.C.

API (American Petroleum Institute). 1980. Guide to water quality standards of the United States. API, Environmental Affairs Department, Publication 4321, Washington, D.C.

Arruda, J. A., G. R. Marzolf, and R. T. Faulk. 1983. The role of suspended sediment in the nutrition of zooplankton in turbid reservoirs. Ecology 64:1225–1235.

Austin, R. W. 1974. Problems in measuring turbidity as a water quality parameter. Pages 23–54 *in* Proceedings of seminar on methodology for monitoring the marine environment. U.S. Environmental Protection Agency, Office of Research and Development, EPA-600/4-74-004, Washington, D.C.

Bachman, R. A. 1984. Foraging behavior of free-ranging wild and hatchery brown trout in a stream. Transactions of the American Fisheries Society 113: 1–32.

Bachmann, R. W. 1958. The ecology of four north Idaho trout streams with reference to the influence of forest road construction. Master's thesis. University of Idaho, Moscow.

Bell, M. C. 1984. Fisheries handbook of engineering requirements and biological criteria, 2nd edition. U.S. Army Corps of Engineers, Portland, Oregon.

Berg, L. 1982. The effect of exposure to short-term pulses of suspended sediment on the behavior of juvenile salmonids. Pages 177–196 *in* G. F. Hartman et al., editors. Proceedings of the Carnation Creek workshop: a ten-year review. Department of Fisheries and Oceans, Pacific Biological Station, Nanaimo, Canada.

Berg, L., and T. G. Northcote. 1985. Changes in territorial, gill-flaring, and feeding behavior in juvenile coho salmon (*Oncorhynchus kisutch*) following short-term pulses of suspended sediment. Canadian Journal of Fisheries and Aquatic Sciences 42:1410–1417.

Beschta, R. L. 1980. Turbidity and suspended sediment relationships. Pages 271–282 *in* Proceedings of the symposium on watershed management '80. American Society of Civil Engineers, New York.

Bisson, P. A., and R. E. Bilby. 1982. Avoidance of suspended sediment by juvenile coho salmon. North American Journal of Fisheries Management 2:371–374.

Brannon, E. L., R. P. Whitman, and T. P. Quinn. 1981. Report on the influence of suspended volcanic ash on the homing behavior of adult chinook salmon (*Oncorhynchus tshawytscha*). Final report to U.S. Department of the Interior, Office of Water Research and Technology, Washington, D.C.

Brezonik, P. L. 1978. Effect of organic color and turbidity on Secchi disk transparency. Journal of the Fisheries Research Board of Canada 35:1410–1416.

Cairns, J., Jr. 1968. Suspended solids standards for the protection of aquatic organisms. Engineering Bulletin Purdue University 12:16–27.

Campbell, H. J. 1954. The effect of siltation from gold dredging on the survival of rainbow trout and eyed eggs in Powder River, Oregon. Oregon Game Commission, Portland, Oregon.

Carlson, R. W. 1984. The influence of pH, dissolved oxygen, suspended solids or dissolved solids upon ventilatory and cough frequencies in the bluegill *Lepomis macrochirus* and brook trout *Salvelinus fontinalis*. Environmental Pollution Series A Ecological and Biological 34:149–169.

Chapman, D. W. 1966. The relative contributions of aquatic and terrestrial primary producers to the trophic relations of stream organisms. Pages 116–130 *in* K. W. Cummins et al., editors. Special publications of the Pymatuning Laboratory of Field Biology, volume 4. University of Pittsburgh, Pittsburgh, Pennsylvania.

Chapman, D. W., and R. L. Demory. 1963. Seasonal changes in the food ingested by aquatic insect larvae and nymphs in two Oregon streams. Ecology 44: 140–146.

DFO (Department of Fisheries and Oceans). 1983. A rationale for the suspended solids standards for Yukon streams subject to placer mining. Report to Interdepartmental Committee on Placer Mining, New Westminster, Canada.

Duchrow, R. M., and W. H. Everhart. 1971. Turbidity measurement. Transactions of the American Fisheries Society 100:682–690.

Earhart, H. G. 1984. Monitoring total suspended solids by using nephelometry. Environmental Management 8:81–86.

EIFAC (European Inland Fisheries Advisory Commission). 1964. Water quality criteria for European freshwater fish. Report on finely divided solids and inland fisheries. EIFAC (European Inland Fisheries Advisory Commission) Technical Paper 1.

Farnworth, E. G., and seven coauthors. 1979. Impacts of sediment and nutrients on biota in surface waters of the United States. U.S. Environmental Protection Agency, EPA-600/3-79-105, Athens, Georgia.

Gammon, J. R. 1970. The effect of inorganic sediment on stream biota. U.S. Environmental Protection Agency, Water Pollution Control Research Series 18050 DWC 12/70, Washington, D.C.

Gardner, M. B. 1981. Effects of turbidity on feeding rates and selectivity of bluegills. Transactions of the American Fisheries Society 110:446–450.

Gibbs, R. J. 1974. Fundamentals of turbidity measurements in nature. Pages 17–22 *in* Proceedings of National Oceanographic Instrumentation Center turbidity workshop, May 1974. National Oceanic and Atmospheric Administration, National Ocean Survey, Washington, D.C.

Gradall, K. S., and W. A. Swenson. 1982. Responses of brook trout and creek chubs to turbidity. Transactions of the American Fisheries Society 111:392–395.

Hecky, R. E. 1984. Thermal and optical characteristics of Southern Indian Lake before, during, and after impoundment and Churchill River diversion. Canadian Journal of Fisheries and Aquatic Sciences 41:579–590.

Hecky, R. E., and S. J. Guildford. 1984. Primary productivity of Southern Indian Lake before, during, and after impoundment and Churchill River diversion. Canadian Journal of Fisheries and Aquatic Sciences 41:591–604.

Heimstra, N. W., D. K. Damkot, and N. G. Benson. 1969. Some effects of silt turbidity on behavior of juvenile largemouth bass and green sunfish. U.S. Fish and Wildlife Service, Bureau of Sport Fisheries and Wildlife Technical Paper 20, Washington, D.C.

Herbert, D. W. M., J. S. Alabaster, M. C. Dart, and R. Lloyd. 1961. The effect of china-clay wastes on trout streams. International Journal of Air and Water Pollution 5:56–74.

Herbert, D. W. M., and J. C. Merkens. 1961. The effect of suspended mineral solids on the survival of trout.

International Journal of Air and Water Pollution 5: 46–55.

Herbert, D. W. M., and J. M. Richards. 1963. The growth and survival of fish in some suspension of solids of industrial origin. International Journal of Air and Water Pollution 7:297–302.

Hill, R. D. 1974. Mining impacts on trout habitat. Pages 47–57 *in* Proceedings of a symposium on trout habitat research and management. Appalachian Consortium Press, Boone, North Carolina.

Hollis, E. H., J. G. Boone, C. R. LeLose, and G. J. Murphy. 1964. A literature review of the effects of turbidity and siltation on aquatic life. Maryland Department of Chesapeake Bay Affairs, Staff report, Annapolis.

Jackson, T. A., and R. E. Hecky. 1980. Depression of primary productivity by humic matter in lake and reservoir waters of the boreal forest zone. Canadian Journal of Fisheries and Aquatic Sciences 37:2300–2317.

Judy, R. D., Jr., P. N. Seeley, T. M. Murray, S. C. Svirsky, M. R. Whitworth, and L. S. Ishinger. 1984. 1982 national fisheries survey. Volume I, technical report: initial findings. U.S. Fish and Wildlife Service Biological Services Program FWS-OBS-84/06.

Kunkle, S. H., and G. H. Comer. 1971. Estimating suspended sediment concentrations in streams by turbidity measurements. Journal of Soil and Water Conservation 26:18–20.

Langer, O. E. 1980. Effects of sedimentation on salmonid stream life. *In* K. Weagle, editor. Report on the technical workshop on suspended solids and the aquatic environment. Department of Indian Affairs and Northern Development (Contract Ott-80-019), Whitehorse, Canada.

LaPerriere, J. D., S. M. Wagener, and D. M. Bjerklie. 1985. Gold-mining effects on heavy metals in streams, Circle Quadrangle, Alaska. Water Resources Bulletin 21:245–252.

Lloyd, D. S., J. P. Koenings, and J. D. LaPerriere. 1987. Effects of turbidity in fresh waters of Alaska. North American Journal of Fisheries Management 7:18–33.

McCabe, G. D., and W. J. O'Brien. 1983. The effects of suspended silt on feeding and reproduction of *Daphnia pulex*. American Midland Naturalist 110: 324–337.

McCart, P. J., P. M. Cross, R. Green, D. W. Mayhood, P. T. P. Tsui, and R. H. Green. 1980. Effects of siltation on the ecology of Ya-Ya Lake, N.W.T. Department of Indian Affairs and Northern Development, Northern Affairs Program, Environmental Studies 13, Ottawa, Canada.

McIntire, C. D. 1973. Periphyton dynamics in laboratory streams: a simulation model and its implications. Ecological Monographs 43:399–420.

McLeay, D. J., G. L. Ennis, I. K. Birtwell, and G. F. Hartman. 1984. Effects on arctic grayling (*Thymallus arcticus*) of prolonged exposure to Yukon placer mining sediment: a laboratory study. Canadian Technical Report of Fisheries and Aquatic Sciences 1241.

McLeay, D. J., A. J. Knox, J. G. Malick, I. K. Birtwell, G. Hartman, and G. L. Ennis. 1983. Effects on arctic grayling (*Thymallus arcticus*) of short-term exposure to Yukon placer mining sediments: laboratory and field studies. Canadian Technical Report of Fisheries and Aquatic Sciences 1171.

Milhous, R. T. 1982. Effect of sediment transport and flow regulation on the ecology of gravel-bed rivers. Pages 819–842 *in* R. D. Hey, J. C. Bathurst, and C. R. Thorne, editors. Gravel-bed rivers. John Wiley & Sons, New York.

Muncy, R. J., G. L. Atchison, R. V. Bulkley, B. W. Menzel, L. G. Perry, and R. C. Summerfelt. 1979. Effects of suspended solids and sediment on reproduction and early life of warmwater fishes: a review. U.S. Environmental Protection Agency, EPA-600/3-79-042, Corvallis, Oregon.

NAS (National Academy of Sciences) and NAE (National Academy of Engineering). 1973. Water quality criteria 1972. U.S. Environmental Protection Agency Ecological Research Series EPA-R3-73-033.

Newport, B. D., and J. E. Moyer. 1974. State-of-the-art: sand and gravel industry. U.S. Environmental Protection Agency, EPA-660/2-74-066, Corvallis, Oregon.

Noggle, C. C. 1978. Behavioral, physiological and lethal effects of suspended sediment on juvenile salmonids. Master's thesis. University of Washington, Seattle.

Olson, W. H., D. L. Chase, and J. N. Hanson. 1973. Preliminary studies using synthetic polymer to reduce turbidity in a hatchery water supply. Progressive Fish-Culturist 35:66–73.

Peterson, L. A., G. E. Nichols, N. B. Hemming, and J. A. Glaspell. 1985. Alaska particulates criteria review. Report to Alaska Department of Environmental Conservation, Juneau.

Phinney, H. K. 1959. Turbidity, sedimentation and photosynthesis. Pages 4–12 *in* E. F. Eldridge and J. N. Wilson, editors. Siltation—its sources and effects on the aquatic environment. Proceedings fifth symposium—Pacific Northwest. U.S. Public Health Service, Portland, Oregon.

Pickering, R. J. 1976. Measurement of "turbidity" and related characteristics of natural waters. U.S. Geological Survey, Open-file Report 76-153, Reston, Virginia.

Redding, J. M., and C. B. Schreck. 1980. Chronic turbidity and stress in juvenile coho salmon and steelhead trout. U.S. Forest Service, Pacific Northwest Forest and Range Experiment Station, Report PNW-1705-16, Corvallis, Oregon.

Ritter, J. R., and W. M. Brown III. 1971. Turbidity and suspended-sediment transport in the Russian River basin, California. U.S. Geological Survey, Open-file Report, Menlo Park, California.

Ritter, J. R., and A. N. Ott. 1974. Measurements of turbidity by the U.S. Geological Survey. Pages 23–29 *in* Proceedings of National Oceanographic Instrumentation Center turbidity workshop, May 1974.

National Oceanic and Atmospheric Administration, National Ocean Survey, Washington, D.C.

Robinson, M. 1957. The effects of suspended material on the reproductive rate of *Daphnia magna*. Publications of the Institute of Marine Science, University of Texas 4:265–277.

Schroeder, W. W., G. F. Crozier, and E. C. Blancher. 1981. Comparison of suspended total solid gravimetry to laboratory and *in situ* nephelometric measurement. Estuaries 4:292.

Scullion, J., and R. W. Edwards. 1980. The effect of pollutants from the coal industry on the fish fauna of a small river in the South Wales coalfield. Environmental Pollution Series A Ecological and Biological 21:141–153.

Sherk, J. A., Jr. 1971. The effects of suspended and deposited sediments on estuarine organisms—literature summary and research needs. University of Maryland Natural Resources Institute Contribution 443.

Sigler, J. W. 1980. Effects of chronic turbidity on feeding, growth and social behavior of steelhead trout and coho salmon. Doctoral dissertation. University of Idaho, Moscow.

Sigler, J. W., T. C. Bjornn, and F. H. Everest. 1984. Effects of chronic turbidity on density and growth of steelheads and coho salmon. Transactions of the American Fisheries Society 113:142–150.

Smith, F. J., and J. L. Sykora. 1976. Early developmental effects of lime-neutralized iron hydroxide suspensions on brook trout and coho salmon. Transactions of the American Fisheries Society 105:308–312.

Sorensen, D. L., M. J. McCarthy, E. J. Middlebrooks, and D. B. Porcella. 1977. Suspended and dissolved solids effects on freshwater biota: a review. U.S. Environmental Protection Agency, EPA-600/3-77-042, Corvallis, Oregon.

Stern, E. M., and W. B. Stickle. 1978. Effects of turbidity and suspended material in aquatic environments: literature review. U.S. Army Corps of Engineers, Waterways Experiment Station, Technical Report D-78-21, Vicksburg, Mississippi.

Stober, Q. J., B. D. Ross, C. L. Melby, P. A. Dinnel, T. H. Jagielo, and E. O. Salo. 1981. Effects of suspended volcanic sediment on coho and chinook salmon in the Toutle and Cowlitz rivers. University of Washington, Fisheries Research Institute, FRI-UW-8124, Seattle.

Sumner, F., and O. R. Smith. 1940. Hydraulic mining and debris dams in relation to fish life in the American and Yuba rivers of California. California Fish and Game 26:1–22.

Swenson, W. A. 1978. Influence of turbidity on fish abundance in western Lake Superior. U.S. Environmental Protection Agency, EPA-600/3-78-067, Duluth, Minnesota.

Sykora, J. L., E. J. Smith, and M. Synak. 1972. Effect of lime neutralized iron hydroxide suspensions on juvenile brook trout (*Salvelinus fontinalis* Mitchill). Water Research 6:935–950.

Tarzwell, C. M. 1957. Water quality criteria for aquatic life. Pages 246–272 *in* C. M. Tarzwell, editor. Transactions of a seminar on biological problems in water pollution. U.S. Department of Health, Education and Welfare, Robert A. Taft Sanitation Engineering Center, Cincinnati, Ohio.

Thurston, R. V., R. C. Russo, C. M. Fetterolf, Jr., T. A. Edsall, and Y. M. Barber, Jr., editors. 1979. A review of the EPA red book: quality criteria for water. American Fisheries Society, Water Quality Section, Bethesda, Maryland.

Tilzer, M. M., C. R. Goldman, R. C. Richards, and R. C. Wrigley. 1976. Influence of sediment inflows on phytoplankton primary productivity in Lake Tahoe (California–Nevada). Internationale Revue der Gesamten Hydrobiologie 61:169–181.

Toland, D. 1984. Suspended solids in mainstem drainages downstream from placer mines, Fairbanks and vicinity, Alaska, August 3–17, 1983. Alaska Department of Environmental Conservation, Environmental Quality Monitoring and Laboratory Operations, Juneau.

Truhlar, J. F. 1976. Determining suspended sediment loads from turbidity records. Pages 7-65–7-74 *in* Proceedings of the third federal interagency sedimentation conference. Water Resources Council, Denver, Colorado.

USEPA (U.S. Environmental Protection Agency). 1976. Quality criteria for water. USEPA, Office of Water and Hazardous Materials, EPA-440/9-76-023, Washington, D.C.

USEPA (U.S. Environmental Protection Agency). 1983. Turbidity. Pages 180.1-1–180.1-4 *in* Methods for chemical analysis of water and wastes. USEPA, Office of Research and Development, EPA-600/4-79-020, Cincinnati, Ohio.

USFWPCA (U.S. Federal Water Pollution Control Administration). 1968. Water quality criteria. USFWPCA, Washington, D.C.

Van Nieuwenhuyse, E. E., and J. D. LaPerriere. 1986. Effects of placer gold mining on primary production in subarctic streams of Alaska. Water Resources Bulletin 22:91–99.

Vanous, R. D., P. E. Larson, and C. C. Hach. 1982. The theory and measurement of turbidity and residue. Pages 163–234 *in* R. A. Minear and L. H. Keith, editors. Water analysis, volume 1. Inorganic species, part 1. Academic Press, New York.

Vinyard, G. L., and W. J. O'Brien. 1976. Effects of light and turbidity on the reactive distance of bluegill (*Lepomis macrochirus*). Journal of the Fisheries Research Board of Canada 33:2845–2849.

Wallen, I. E. 1951. The direct effect of turbidity on fishes. Oklahoma Agricultural and Mechanical College Bulletin 48(2):1–27.

Whitman, R. P., T. P. Quinn, and E. L. Brannon. 1982. Influence of suspended volcanic ash on homing behavior of adult chinook salmon. Transactions of the American Fisheries Society 111:63–69.

Wilber, C. G. 1969. The biological aspects of water pollution. Charles C Thomas, Springfield, Illinois.

Wilber, C. G. 1983. Turbidity in the aquatic environment: an environmental factor in fresh and oceanic waters. Charles C Thomas, Springfield, Illinois.

Wilson, J. N. 1957. Effects of turbidity and silt on aquatic life. Pages 235–239 *in* C. M. Tarzwell, editor. Transactions of a seminar on biological problems in water pollution. U.S. Department of Health, Education and Welfare, Robert A. Taft Sanitation Engineering Center, Cincinnati, Ohio.

Witte, W. G., and seven coauthors. 1982. Influence of dissolved organic materials on turbid water optical properties and remote-sensing reflectance. Journal of Geophysical Research 87:441–446.